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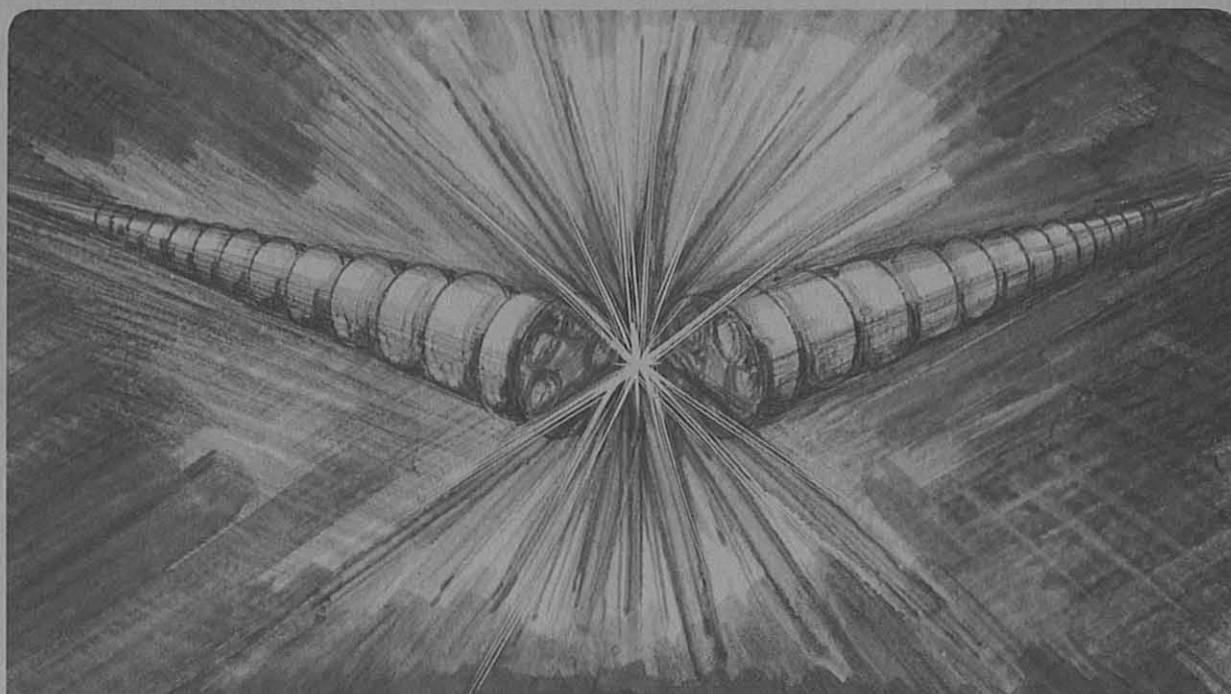
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The Effects of Insertion Devices on Beam Dynamics in the ALS

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1. Introduction

Third generation synchrotron radiation sources, such as the Advanced Light Source (ALS) [1], are specifically designed to operate with long undulators that produce very high brightness beams of synchrotron radiation. Including such devices in the storage ring magnet lattice introduces extra linear and nonlinear fields that are intrinsic to the undulator. These fields break the symmetry of the lattice and provide driving forces for nonlinear resonances, thereby perturbing the dynamics of the electron motion, particularly at large amplitudes. The main impact of these perturbations is on the beam lifetime, arising out of a reduction of both the transverse acceptance and the momentum acceptance. In this paper, we present the results of an ongoing study of these effects as they relate to the performance of the ALS.

2. Background

In the past few years, there has been a growing realization that insertion devices in low emittance storage rings play a significant role in the beam dynamics of the circulating electron (or positron) beam [2,3]. The source of the effect has two components. Firstly, the undulator produces a linear, or focusing, force. In the case of an ideal planar undulator, whose fields are defined in eq. 1, the focusing is in the direction perpendicular to the plane of electron oscillations, and has a strength proportional to the length of the device and to the square of the field it produces.

$$\begin{aligned} B_y &= B_0 \cosh k_x x \cosh k_y y \cos kz \\ B_x &= \frac{k_x}{k_y} B_0 \sinh k_x x \sinh k_y y \cos kz \\ B_z &= \frac{k_y}{k_x} B_0 \cosh k_x x \sinh k_y y \sin kz \end{aligned} \quad (1)$$

where $k_x^2 + k_y^2 = k^2 = \left(\frac{2\pi}{\lambda_u}\right)^2$

and λ_u is the undulator period.

Since this focusing effect is linear, it is possible to compensate for it locally, that is, within the insertion device straight section [4], if four families of quadrupoles (or two movable families) are available. This is not an option in the ALS, where, as we show in Fig. 1, there are only two, fixed, quadrupole families per straight section.

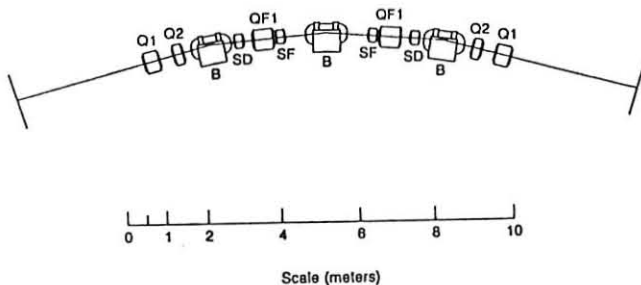


Fig. 1. One unit cell (one-twelfth) of the ALS magnet lattice.

Secondly, there are nonlinear fields whose strengths are proportional to the length of the device, to the square of the field, and inversely to the square of the period length. Since we attempt to make each undulator as long as possible, their lengths turn out to be about the same (in the case of the ALS about 5 m), therefore their linear strengths scale as B_0^2 , and their nonlinear strengths as B_0^2/λ_u^2 .

The main impact on beam dynamics caused by insertion devices will be on beam lifetime. Here we are concerned with two aspects: the machine acceptance (defined by the on-momentum dynamic aperture), which determines the elastic gas scattering lifetime; and the maximum momentum acceptance, which determines the Touschek and bremsstrahlung lifetimes. Of course, horizontal aperture is also important for injection into the ALS. However, it is envisioned that the insertion devices will be "switched off" (by increasing their gap) during the injection process.

3. Compensation Techniques

With two families of quadrupoles available in each straight section, there are a limited number of compensation schemes available. Since we find that the beam dynamics is particularly sensitive to the tune of the lattice, we choose to correct the tune. Three tune compensation schemes have been investigated:

- The change in tune introduced by the undulator is corrected using all straight section QFs as one variable and all straight section QDs as the second. We call this "global" tune compensation.
- Since the undulator gives focusing only in the vertical plane, we compensate for the vertical tune change locally, with the QDs adjacent to the undulator, but maintain the radial superperiodicity by correcting the radial tune globally. We call this technique "global QF / local QD" tune compensation.
- Finally, we can correct both tunes using just the pairs of quadrupoles adjacent to the insertion device itself. We call this method "local" tune compensation.

In addition to tune compensation, we can arrange to transport the beta functions, at the point where they leave the bending magnet, such that they have zero slope ($\alpha_x = \alpha_y = 0$) at the center of the insertion device, utilizing the quadrupoles adjacent to the device. Symmetry ensures that the beta functions remain unchanged around the rest of the machine. The tune is restored by using the quadrupoles in the remaining straights. We call this technique "alpha matching."

4. Effects of the Undulators on the Dynamic Aperture

In order to assess the effects of a single undulator on the performance of the ALS, we choose undulator parameters that combine the worst linear and nonlinear properties of the devices being considered. That is, we take an undulator with the shortest period 3.65 cm, but operating at a field level of 1.2 T. (It should be noted that these parameters cannot be achieved when we introduce the constraint of a 14 mm magnet gap) The effect of this device, under the different compensation schemes described above, on the dynamic aperture of an otherwise perfect machine is shown in Fig. 2. It can be seen that the effect is indeed dramatic, but is not particularly sensitive to the compensation scheme adopted. Also note that the minimum acceptance of the machine is determined by the aperture defined by the insertion device vacuum chamber (± 5 mm), which, when projected to the tracking point, translates to ± 4 mm.

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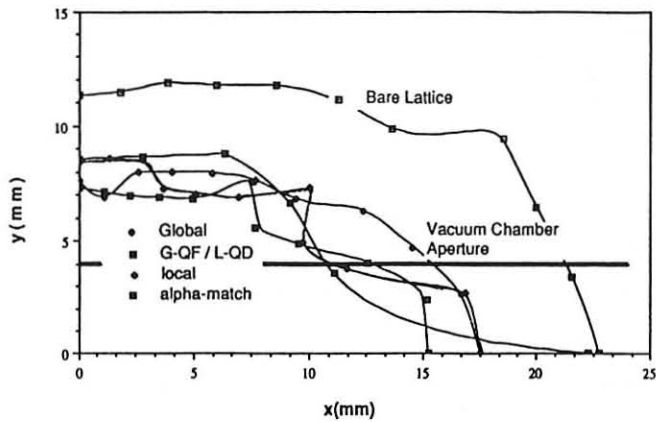


Fig. 2 Effect of U3.65, with $B = 1.2$ T, on the dynamic aperture.

We next look at four consecutive undulators. The reason for this choice is that the arrangement looked particularly troublesome in some initial studies on full linear matching. Here, in the interest of computer time, we limit our attention to two compensation techniques: the local technique and the global QF / local QD technique. Again, as we show in Fig. 3, there is little to choose between the two methods, and the minimum acceptance is still determined by the vacuum vessel aperture.

Encouraged by these results we choose one compensation technique, the local tune correction method, in order to expand the study to more realistic devices (those described in ref. 1), whose properties are summarized in Table 1. These devices were arranged in the lattice in descending order of period length, with each set to its maximum field. This arrangement places the undulators with the strongest linear effects in adjacent straight sections, a combination thought to give the worst effects on dynamic aperture. After ascertaining that the resulting aperture is acceptable (see Fig. 4), a second group of four devices was added, repeating the pattern described above, with the two sets separated by one empty straight. (This arrangement recognizes that there are at least two straight sections in the ALS, the injection straight and the rf straight, that cannot accommodate 5 m long insertion devices.) The effect on the dynamic aperture of both four and eight undulators is shown in Fig. 4. Still we find that the acceptance is limited by the vacuum vessel.

Table 1 Summary of Undulator Properties

Name	Period (cm)	No. of Periods	Maximum Field (Tesla)	K_{\max}
U3.65	3.65	134	0.61	2.10
U5.0	5.00	98	0.83	3.88
U9.0	9.00	53	1.15	9.64
U20.0	20.00	23	1.10	20.63

All the results shown above assume a perfect storage ring magnet lattice. What happens when we include magnetic imperfections [5], magnet placement errors and a corrected closed orbit distortion [6]? In the first place, the dynamic aperture of the storage ring without any insertion devices is reduced. This, and the additional effect of our arrangement of eight undulators, is shown in Fig. 5. Again we see that the minimum acceptance of the ring is determined by the insertion device vacuum chamber.

Before pursuing this study into momentum space, it is reasonable to try to understand why the addition of more and more undulators does not lead to the total collapse of the dynamic aperture.

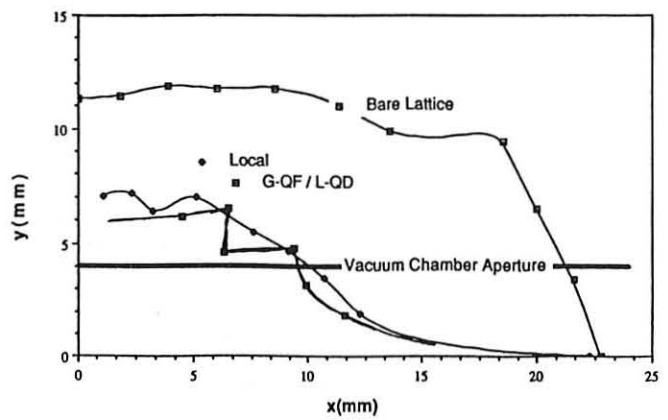


Fig. 3 Effect of 4 consecutive undulators. Local and global/local correction schemes.

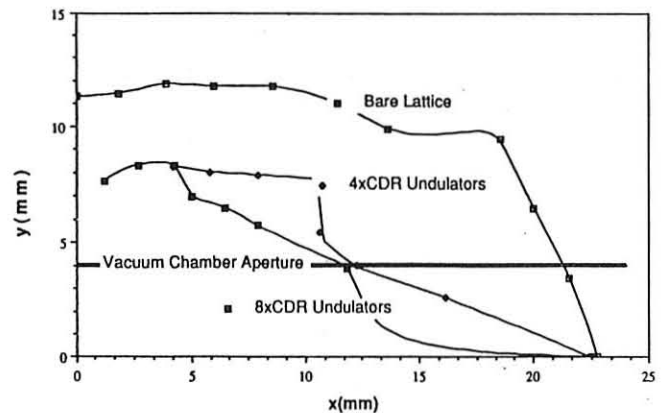


Fig. 4 Effect of 4 and 8 CDR undulators, local tune compensation.

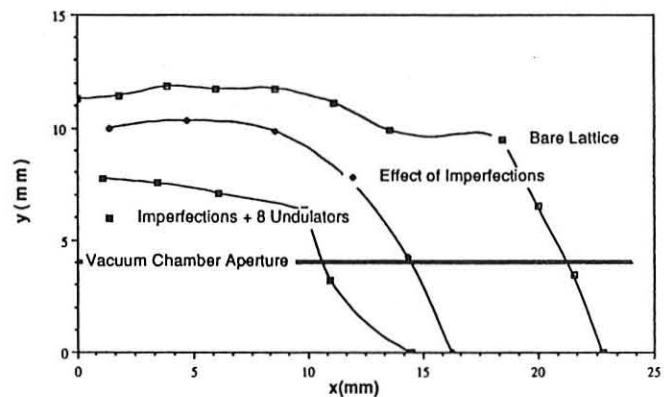


Fig. 5 Effect of magnet imperfections and undulators.

Our studies have shown (see refs. 1 and 3) that the single most important parameter in causing the reduction in dynamic aperture is the distortion of the periodic betatron phase between the very strong sextupoles in the lattice. By measuring the difference in betatron phase between homologous points in each achromat for various arrangements of insertion devices, and comparing this with the phase advance in the ideal lattice, it might be possible to gauge, at least

qualitatively, the reduction in the dynamic aperture. When we use this technique to analyze the effects of one, two or four consecutive devices, compensated using the local tune correction technique, we find essentially no difference in the mean value of the phase distortions. Also, the amplitude of the phase distortion, when compared with those caused by magnetic imperfections (see Table 2), explains qualitatively the relative impact on the two transverse planes.

Table 2 RMS Phase Distortions Introduced by an Insertion Device^{a)}

No. of devices	Horizontal Plane	Vertical Plane
0 (Errors only)	2.09×10^{-3}	3.80×10^{-3}
1	1.12×10^{-3}	2.95×10^{-2}
2	0.98×10^{-3}	3.07×10^{-2}
4	1.06×10^{-3}	2.99×10^{-2}

^{a)} Device type: Undulator U3.65, set to a field of 1.2 T.

We have carried this analysis further by Fourier analyzing the betatron phase distortion. An example that shows the harmonic content of the horizontal phase distortion, for the cases of one and four consecutive undulators, is shown in Fig. 6. Again we see little difference between the two cases; the same conclusion is reached for the vertical plane. Thus, if our conjecture is correct that it is the phase distortion between the strong sextupoles that is the main cause of the reduction in dynamic aperture, we should not expect to see a dramatic collapse as we add more devices.

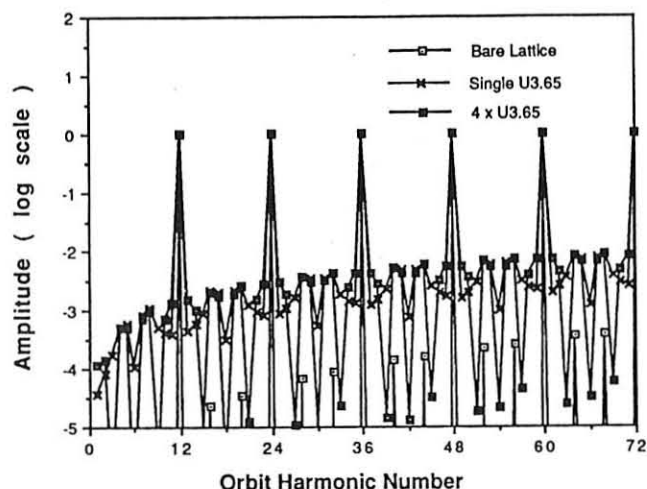


Fig. 6 Fourier spectrum of horizontal betatron phase between sextupoles.

5. Effects of Undulators on the Momentum Acceptance

Finally, we have investigated the momentum acceptance of the storage ring by measuring the stability of the particle trajectory after a discrete change in energy at particular places in the lattice. The intent here is to simulate the effect of a Touschek scattering event, or an inelastic scattering from a residual gas molecule. The amplitude of the energy loss is increased until we meet the limit imposed by the rf system ($dp/p = 3.3\%$), or until the particle motion becomes unstable. In the case of the perfect lattice, we find that the particle motion remains stable for momentum changes up to the rf limit, no matter where in the ring the scattering event takes place. However, when we include errors, or insertion devices, or both, we see that, when the scattering occurs in the achromat, the particle motion becomes unstable at a momentum deviation below the rf limit. For the machine with errors, the limit is between 2.5% and 3.3%. When we add our complement of eight undulators, this limit drops to around 2.5%. We also found that this limit is very sensitive to machine tune, with a limit of 1.5% being observed at the nominal tune of $\nu_x/\nu_y = 14.28/8.18$, compared with 2.4% at $\nu_x/\nu_y = 14.29/8.26$.

The mechanism by which the particles are lost is not yet fully understood. It requires that synchrotron motion be included in the simulation, and the observed step changes in vertical motion are reminiscent of observations in simulations of the beam-beam interaction. This effect will be investigated further. The main implication for the performance of the ALS is in the Touschek lifetime, which scales as the third power of the momentum acceptance. (There is also a small effect on the bremsstrahlung lifetime, but this is so long that the decrease has no significant impact on the overall lifetime.) We have estimated the effect of the changes in momentum acceptance in the achromat using ZAP [7], including all the components that affect the beam lifetime: elastic and inelastic gas scattering, and Touschek scattering. Figure 7 shows the estimated impact on the beam decay in the ALS for single-bunch operation. The effect on multibunch operation, where the contribution from the Touschek effect is smaller, is less pronounced.

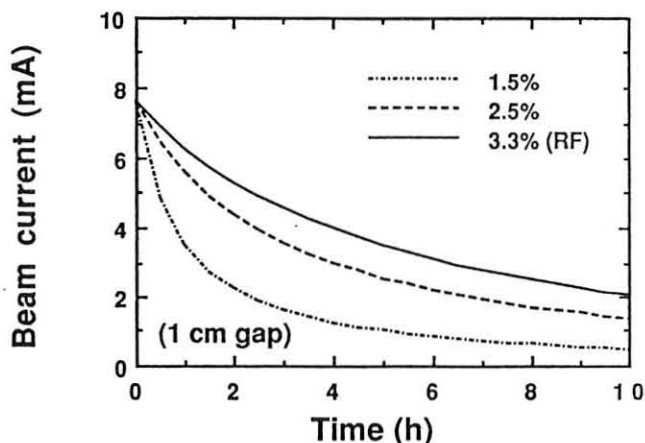


Fig. 7 ALS beam current decay (single bunch).

6. Summary

We have shown that introduction of undulators into the ALS causes a significant reduction in dynamic aperture. However, the effect is similar to that which we expect from the storage ring when we include realistic magnetic imperfections, magnet misalignments, and a corrected closed orbit. Moreover, when we add undulators into the imperfect machine there is little further degradation of the dynamic aperture. In all cases the machine acceptance will be determined by the physical (vacuum aperture), rather than the diminished dynamic aperture. Thus, we do not expect the insertion devices to impact the elastic gas scattering lifetime of the ALS. The momentum acceptance of the storage ring is also seriously affected by the undulators. This will impact the Touschek lifetime of the ALS. However, at the levels predicted by our study, the resulting overall beam lifetimes are still acceptable.

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